DIRECTIONAL EJECTION OF LIQUID DROPLETS THROUGH SECTORING HALF-WAVE-BAND SOURCES OF SELF-FOCUSING ACOUSTIC TRANSDUCER

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ABSTRACT

This paper describes a technique to produce liquid droplets in almost any direction with a Self Focusing Acoustic Transducer (SFAT) built on a thin low stress silicon nitride diaphragm with a piezoelectric ZnO film and patterned electrodes. Sectoring of the SFAT annular-rings, half-wave-band sources (to create a piezoelectrically inactive area) causes the droplet ejections to be nonperpendicular to the liquid surface. The direction of the droplet ejections depends on the size of the open area (i.e., piezoelectrically inactive area) within the circular area of the half-wave-band sources. Droplets are ejected from the center part of the annular rings toward the open inactive area. Various openings of pie shape (up to 90^{o}) have been made and tested to show that the ejection direction becomes less vertical as the piezoelectrically inactive area in the transducer increases.

INTRODUCTION

The demand for high resolution/speed ink-jet printing at low cost is ever increasing not only for paper printing but also for DNA/protein printing/spotting. Almost all of the current ink jet printers eject ink droplets through nozzles, in which case the ejection direction is always perpendicular to the nozzle surface. The inability to control the ejection direction (with nozzle-based ejection) requires the printhead to be moved, if a spot on a paper is to be covered by more than one type of ink. A focused acoustic beam can eject liquid droplets without any nozzle, and an acoustic lens [1-2] or a self-focusing through constructive wave interference [3-4] has been used to focus acoustic wave for liquid ejection. When self-focusing through Fresnel annular rings of half-wave-band sources is used [5], the annular rings can be sectored to generate acoustic pressure directed at almost any direction. This paper describes the design, fabrication and experimental results on the sectored Fresnel rings for directional ejection.

DESIGN AND FABRICATION

Self Focusing Acoustic Transducer (SFAT) uses a set of complete annular rings, which act as half-wave-band sources to produce an intensified acoustic radiation pressure (at the focal point) that is directed perpendicularly to the liquid surface [3-4]. The large acoustic pressure ejects liquid droplets in a direction perpendicular to the plane of the annular rings. The SFAT has been shown to eject micron-sized liquid droplets from the free-liquid surface.

When the annular rings are sectored as shown in Fig. 1, the acoustic radiation pressure at the focal point is unbalanced in the plane of the liquid top surface, and the droplet ejection happens in a direction that is oblique to the liquid surface plane. The simulation of the vertical particle displacement on the focal plane shows that as the annular rings are carved out with a pie shaped opening, the vertical displacement becomes less intensified, while the lateral displacement becomes larger, at the focal point, and ejection can happen at an oblique angle as indicated in Fig. 1.

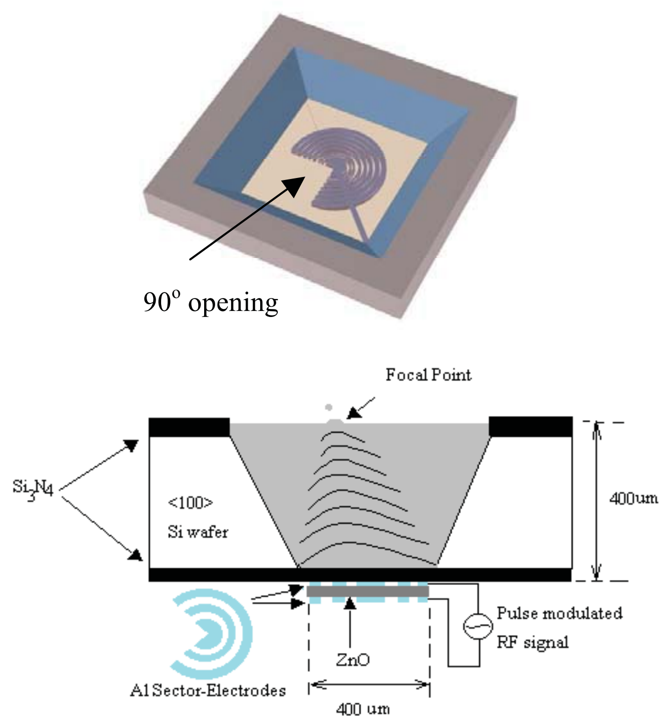

Figure 1. Perspective and cross-sectional views of the 270° sector SFAT producing a directional ejection of liquid droplets.

Though the vertically directed pressure is reduced, the sectored SFAT can exert large enough radiation pressure for liquid droplet ejection at the free-liquid interface. As for the direction of the droplet ejection, the liquid over the transducer part covered by the electrodes receives much more acoustic waves from the transducer

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than that over the no-electrode area (i.e., pie shaped opening area), and the liquid droplet ejection is directed from the electrode area to the open electrode area, as illustrated in Figs. 1 and 2.

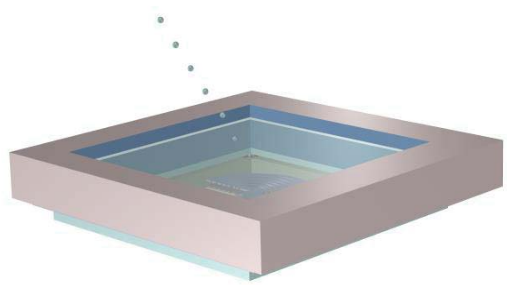


Figure 2. Illustration of the concept for obliquely inclined directional ejection of liquid droplets with a sector SFAT.

A brief fabrication process for the sectored SFAT is illustrated in Fig. 4 and described as follows. After depositing 0.8µm thick LPCVD low stress nitride and patterning the nitride on the wafer backside, 0.5µm thick Al is deposited and patterned for the bottom electrode on the wafer front side. Then, 5µm thick ZnO is sputter deposited from ZnO target, followed by 0.5µm thick Al evaporation and pattering for the top electrodes. Finally, the silicon is removed by KOH from the backside to form 500 x 500 μm^2 diaphragms, the front side being protected with a mechanical jig against KOH.

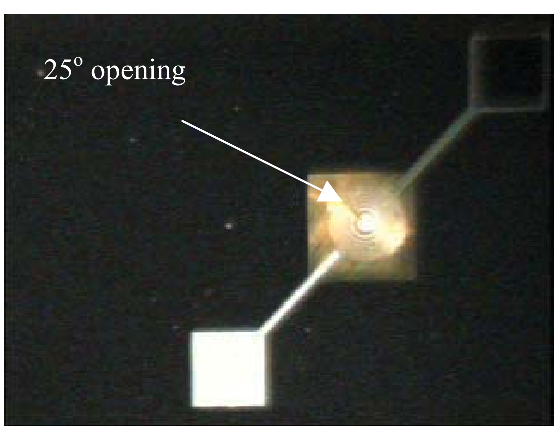


Figure 3. Photo of a fabricated 25 ° sector SFAT.

Figure 3 shows a fabricated sector SFAT that has piezoelectrically inactive area of a pie shape with 25° angle at its apex. Sector SFATs with various pie angles between 25° and 90° have been fabricated and observed to produce varying degree of oblique ejections.

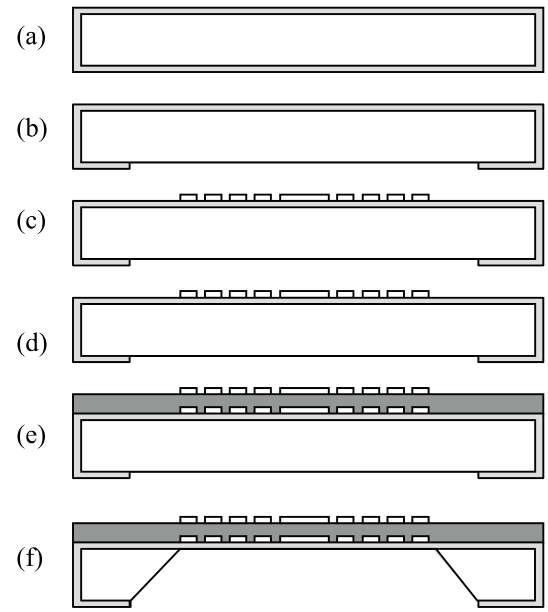


Figure 4. Fabrication processing steps for sector SFAT. (a) Deposit 0.8µm thick Si_xN_y (b) Pattern Si_xN_y at the wafer backside. (c) Deposit and pattern bottom Al electrodes. (d) Sputter-deposit ZnO (e) Deposit and pattern top Al electrodes. (f) Remove the silicon from the backside with the front side protected with a mechanical jig.

EXPERIMENTAL RESULT

The fabricated transducers are tested with a set-up shown in Fig. 5, where pulses of 600 MHz sinusoidal are applied to the transducer. A CCD camera with a microscope is placed horizontally to record the water ejection process through stroboscopically blinking LED to capture the ejection process.

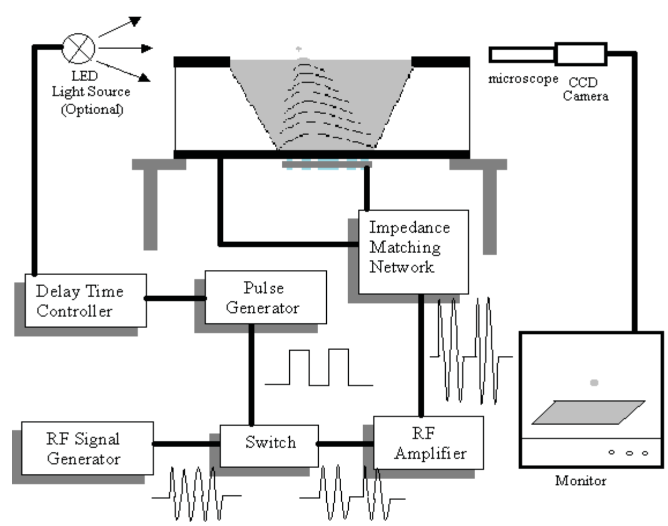
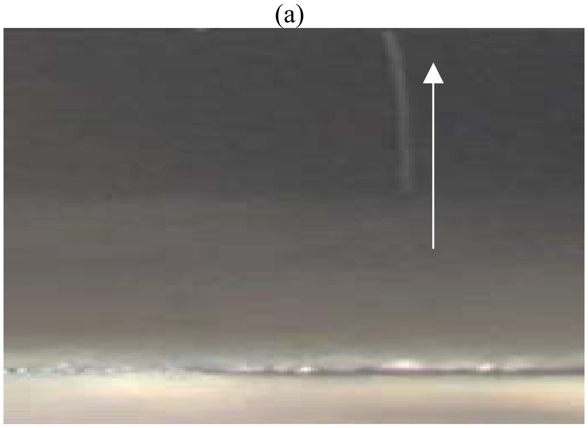


Figure 5. Schematic of the test setup with stroboscopic illumination by LED.

Synchronization of the flash illumination (which lasts about 20 μsec) with the sinusoidal pulse input is achieved by turning on the LED with another pulse source triggered by the pulse generator that turns on and off (i.e., pulses) the sinusoidal signal. By varying the delay time between the illumination of the LED and the RF pulse applied to the transducer, we can observe the ejection process of at any moment.

(a)



(b)

Figure 6. Side-view photos of the trails of liquid droplets ejected by (a) the 270° sector SFAT and (b) the ring SFAT with a set of complete annular rings. The sector SFAT ejects droplets at an angle oblique to the liquid surface, while the ring SFAT ejects droplets perpendicular to the liquid surface.

The trajectory of the directionally ejected microdroplets can easily be affected by an air flow. Thus, flow barriers are used around the device under test.

The 270° sector SFAT (that has 90^o opening) ejects liquid droplets (from the center of a non-sectored pattern) at about 62.5° with respect to the liquid surface, as shown in Figs. 6a and 7. For comparison, a photo of an ejection trail from a non-sectored SFAT (i.e., the one with a set of complete annular rings) is shown in Fig. 6b.

Figure 7 shows the trajectory of the ejected water droplets as well as the minimum size of the ejected water droplets, which is about 10 μm in diameter. The ejecting direction is along the direction from the active area toward the 90° open area. The design and performance of the sectored SFAT is summarized in Table1.

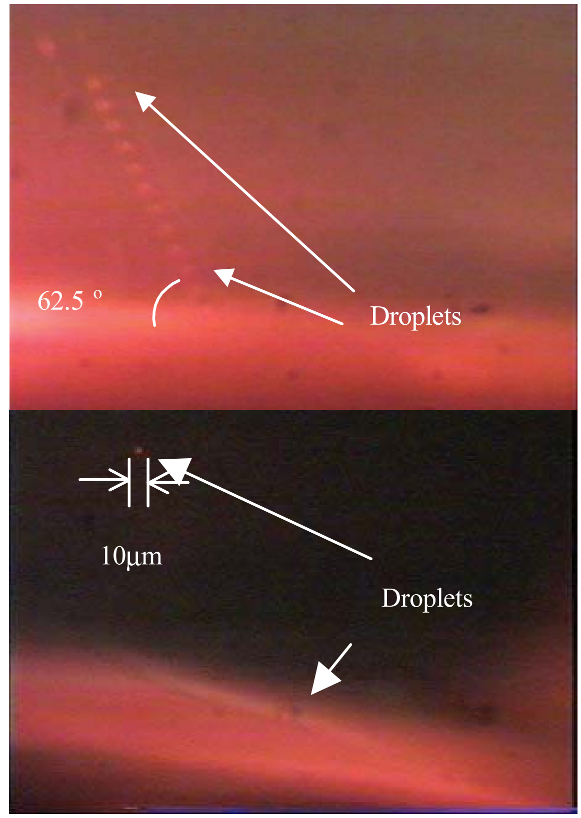
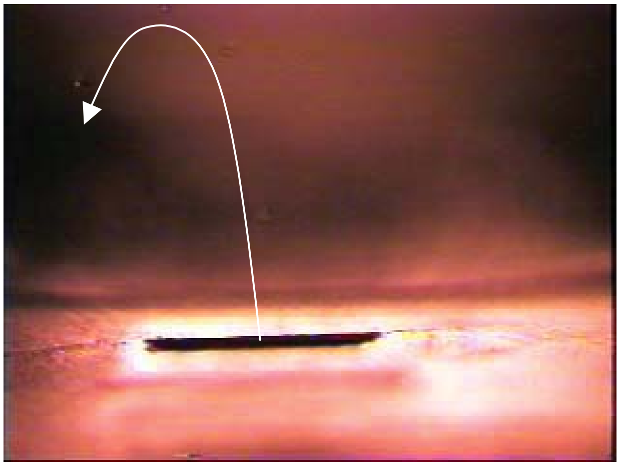


Figure 7. Snapshot photos of liquid droplets ejected by the 270° sector SFAT: upper photo shows a stream of the droplets at 62.5° oblique to the liquid surface; lower photo shows the smallest droplet captured with our current test setup.

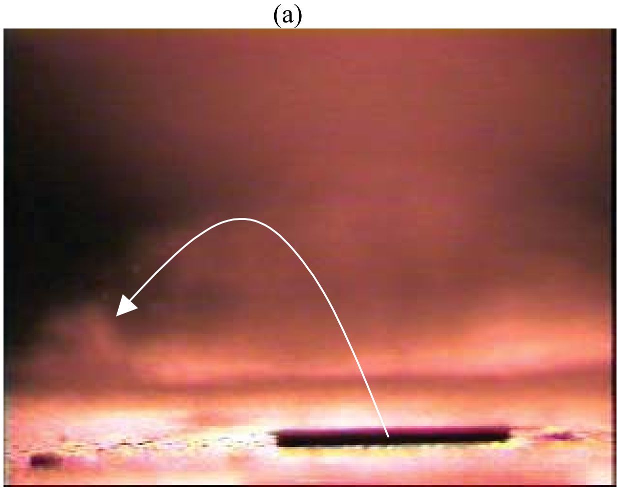
Table1: Design and Performance of the 270° Sector SFAT.

ZnO Thickness	5 μm
Resonant Frequency	600MHz
Focal Length	350 μm
Min. Droplet Size	< 10 μm
Min. RF pulse width	5 μsec
Potential Resolution	>2500dpi

As can be seen in Fig 8, the fabricated 335^o sector SFAT (that has 25^o opening) ejects liquid droplets at 81^o from the direction normal to the liquid surface, while the 320^o (40^o opening) sector SFAT ejects liquid droplets at 73^o. Table2 summarizes the directional ejections for the three different sector SFATs, showing that the ejection becomes less vertical as the piezoelectrically inactive area in the transducer increases, as the apex angle (of the pie carving out the transducer annular rings) increases.



(a)



(b)

Figure 8. Snapshot photos of liquid droplets ejected by (a) the 335° sector SFAT and (b) the 320° sector SFAT, showing marked difference in the ejection directions. The former and the latter eject liquid droplets at 81° and 73° oblique to the liquid surface, respectively.

Table 2. Ejection angle comparison of various sector SFATs.

Apex angle of the inactive pie in sector SFAT	Ejection angle with respect to liquid surface
25°	81°
40°	73°
90°	62.5°

CONCLUSION

We have successfully demonstrated the obliquely inclined directional liquid ejection by various sectored SFATs, which can be designed to produce liquid droplets in any desired direction by adjusting the open angle of the sectored electrodes. This means that one SFAT can potentially print over a relatively large area, and a high resolution printing can be achieved without having to move the ejector array. Also, a spot on a paper can be inked by more than one SFAT containing different inks, again without the need to mechanically move the ejectors.

ACKKNOWLEDGEMENTS

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REFERENCES

[1] S. A. Elrod, B. Hadimooglu, B. T. Khuri-Yakub, E. G. Rawson, E. Richley, C. F. Quate, N. N. Mansour and T. S. Lundgren, "Nozzleless Droplet Formation with Focused Acoustic Beams," Journal of Applied Physics, 65(9), 1989, pp. 3441-3447.

[2] K. Yamaha and H. Shimizu, "Planar-Structure Focusing Lens for Acoustic Microscope," Journal of Acoustic Society Japan, (e) 12, pp.123-129, Mar.1991.

[3] H. Wang and E. S. Kim, "Ejection Characteristics of the Micromachined Acoustic-Wave Liquid Ejector", IEEE International Conference on Solid-State Sensors and Actuators (Sendai, Japan), June 7-10,1999, pp. 1784-1787.

[4] D. Huang and E. S. Kim, "Micromachined Acoustic-Wave Liquid Ejector," IEEE/ASME Journal of Microelectromechanical Systems, vol. 10, pp. 442-449, September 2001.

[5] G. S. Kino, Acoustic Waves: Design Imaging and Analog Signal Processing, Prentice-Hall, Englewood Cliffs, NJ, 1987.